Annual Project Summary
DEEP BOREHOLE TENSOR STRAIN MONITORING, NORTHERN CALIFORNIA

NEHRP Grant 01-HQ-GR-0155

Dr. M.T. Gladwin, Chief Research Scientist
Dr. R.L.Gwyther, Research Geophysicist

Commonwealth Scientific and Industrial Research Organisation
2643 Moggill Rd., Pinjarra Hills, QLD 4069, AUSTRALIA
phone +617 3327 4562
fax +617 3327 4455

II
seismology, geodesy, borehole geophysics

Project Objectives and Approach

This project provides field observations contributing to an understanding of fault processes associated with earthquakes along the San Andreas and Hayward faults. Continuous high precision and high resolution borehole tensor strain data provide an essential complement to long baseline interferometry studies (limited to sampling intervals of weeks), GPS studies, and seismic characterisation of faults.

The project continues a program of maintenance and analysis of deep borehole tensor strain instrumentation initiated at San Juan Bautista in late 1983, expanded by three sites installed in the Parkfield area during December of 1986, by two sites deployed near the Hayward Fault in the San Francisco Bay region in 1992. These instruments consist of a three component plane strain module operating at a strain sensitivity of 10^{-10} and support data logging systems. As deployed they provide data sampling at 30 minute intervals for transmission via satellite for permanent archive purposes. The instruments provided by this project are unique in the program in that they provide continuous tensor strain data of high quality and sensitivity not achievable by any other instrumentation. These data form a critical complement to GPS and geodetic studies (see Figure 1) in assessing strain rates and consequent earthquake risk, as well as investigating fault processes associated with earthquake preparation and postseismic relaxation.

Archived long term baseline data are available for download from *http://www.cat.csiro.au/dem/msg/straincal/straincal.html*. Data are made available in near real time in the USGS Menlo Park computer system (***thecove:/home/mick/QUICKCHECK***). These data supplement long baseline survey data, and permit real time monitoring for short term strain phenomena.

The **immediate objectives** of the project are

- Maintenance of uphole system integrity at 5 Northern Californian sites, with repair or production of replacement uphole electronics if necessary.

- Manual preparation of raw instrument data for permanent archive.
- Analysis of continuous unique low frequency shear strain data (30 minute samples) and modelling studies based on the constraints of these data
- Regular reporting and real time alert response as part of the Parkfield Prediction experiment.
- Archive of processed data for access by the earthquake studies community, and provision of near-real time automatically processed data for inclusion in publicly accessible web pages linked to the USGS web datasets.

The project is carried out in parallel with maintenance of two further sites (Pinon Flat and San Gabriel mountains) in Southern California.

Investigations & Results

Stress transfer on faults

In the 17 year baseline of data from the borehole tensor strain observations, we have identified both piecewise-linear fault slip at intermediate depths of 2 to 5 km, and aseismic episodic slip at shallow depths of 1-2 km. This phenomenon has been observed routinely at both the San Juan Bautista and also the Parkfield segments of the fault.

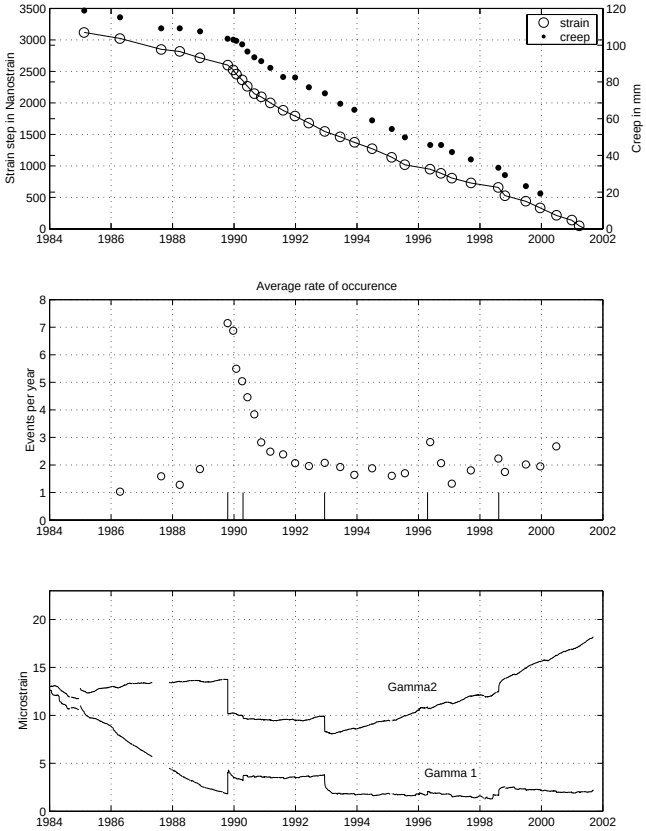

Figure 1. *Top panel*: Accumulated strain and creep due to episodic events at San Juan Bautista. *Middle panel*: Rate of occurrence of the episodic events. Loma Prieta in 1989, Chittenden earthquake in 1990, and slow events in 1992, 1996 and 1998 are indicated by vertical lines. *Bottom panel*: Long term shear strains measured at San Juan Bautista.

Figure 1 shows observations of these events at San Juan Bautista. The aseismic episodic strain events at San Juan Bautista have an event duration of 60 minutes, whilst those at Parkfield have a duration of a few days, and in each case a repeat interval of months. The long term strain rate changes in both regions occur with a repeat interval of a few years, and modelling indicates that these rate changes result from stick-slip behaviour on fault patches of a few kilometers in dimension, situated at depths from 2 - 5 km.

The rate of episodic events at San Juan Bautista changed abruptly after the Loma Prieta earthquake, and a change of rate is also evident after the slow earthquake in December 1992. These data indicate that that the changes in repetition rate of the aseismic, episodic strain events at shallow depths may be linked to the long term changes in rate due to slip at medium depths. Such a link provides a unified mechanism for accommodation of stress transfer processes across the seismogenic zone.

A preliminary model of heterogeneous slip on the fault surface, with some patches exhibiting stick-slip behaviour and other patches failing aseismically, has been developed. The resulting stress from failure on these surfaces at medium depths of 2-5 km is transferred to shallow depths of less than 1km, and leads to the episodic strain events. These data will be presented at Fall AGU in Decmber 2001.

Complex episodic stain and creep events at Parkfield.:

Episodic strain/creep events observed at San Juan Bautista are reliably and consistently characterized as self-similar, and a single failure patch has been previously identified as the source of these events. In contrast, episodic strain events at Parkfield have a range of different characters, indicating differing source process. The subsets of these events are self-similar, and two differing subsets are shown in figures 2 and 3.

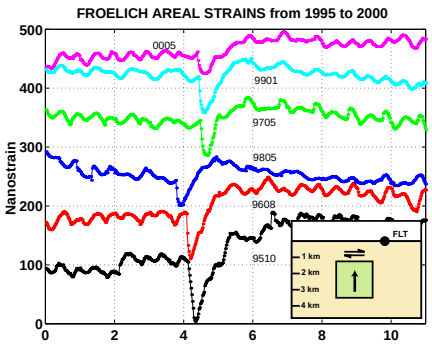

Figure 2 Self similar strain events observed at Frolich, Parkfield. These events are representative of a subset of episodic events observed at Parkfield since 1988

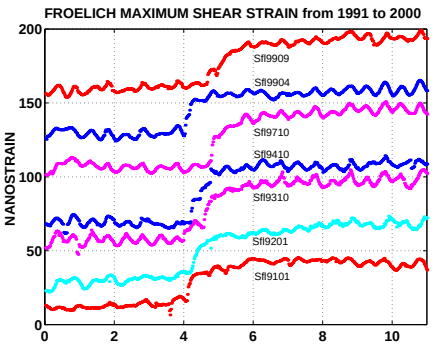

Figure 3 A subset of self similar strain events observed at Frolich, Parkfield. These events are representative of a different subset of episodic events from those shown in Figure 2.

The events observed at Parkfield are associated with surface creep events. However the creep events occur over a longer interval (typically a few days) than the strain events (typically 24 hours) and commence after the observed strain events. These data suggest that slow slip over a period of 24 hours occurs at shallow depth, and this slip then propagates to the surface. Typically the strain events observed at Parkfield have

a significantly longer timescale (24 hours) than those observed at San Juan Bautista (1 hour).

The complexity in character of the episodic events observed at Parkfield is illustrated in Figure 4. In this figure, strains observed at Eades and Frolich are shown in the upper panel, and associated creepmeter records at sites close to Parkfield are shown in the lower panel. Principal strain events occurred on August 21, 28 and 30, with creep events following over the ensuing few days in each case.

Strain data observed on the tensor strainmeter at Chabot near the Hayward fault has not recorded significant changes of strain rate over the past year. However there is now evidence that aseismic strain events with associated tilt and creep may occur at this site, as illustrated by Figure 5, which shows such an event in May 2001.

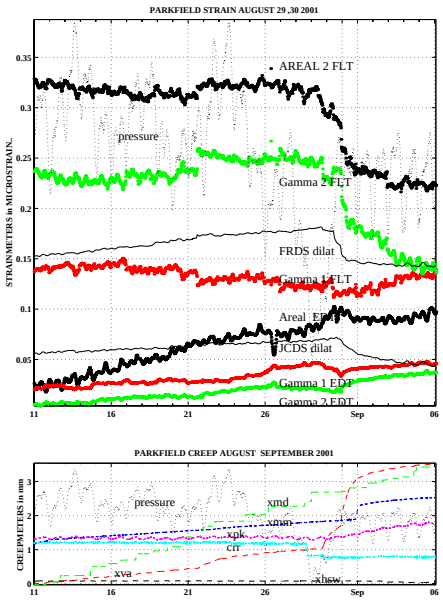

Figure 4 *upper panel:* Strains observed at Parkfield in August/September 2001. *lower panel*: surface creep events observed at this time.

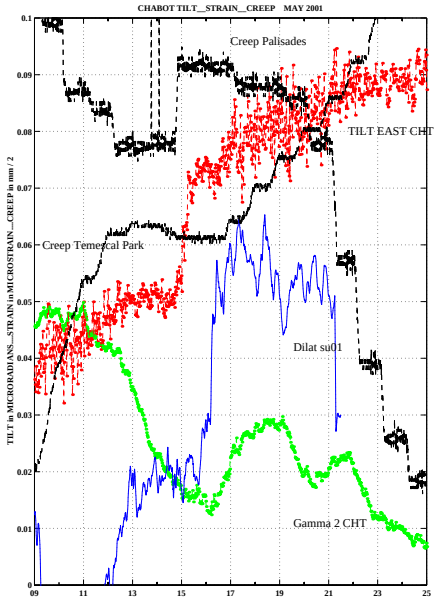

Figure 5. A slow strain event observed at Chabot in the East Bay during May 2001. Associated surface creep events also occurred on nearby creepmeters.

Data Availability

Archived strain data from the Californian sites are stored in both raw component form, and as processed areal and shear strains. A regularly updated archive of data has been maintained in the USGS Menlo Park computer system since 1988. This data is stored in binary files with appended header information (USGS "*bottle*" format).

Home page for access to data plots from all borehole tensor strain instruments is *http://www.cat.csiro.au/dem/msg/straincal/straincal.html*. ***This page also includes facilities for download of raw or processed data from our CSIRO archive***.

Automatically processed near-realtime data is available in *thecove:/home/mick/QUICKCHECK* for users with access to USGS plotting software "*xqp*", and via the USGS crustal deformation web pages in graphical form.

Scientists requiring other access to the archived data should contact Dr. R. Gwyther (+617 3212 4586, email*: r.gwyther@cat.csiro.au*) or Dr. M.T. Gladwin (+617 3212 4562).

Publications

Publications 2000 - 2001

Gwyther,R.L , Gladwin,M.T, & Hart,R.H.G. &M.Mee Focussed Study of Aseismic Fault Processes, *Workshop Abstracts, Earthscope Workshop: Making and Breaking a Continent, October 2001. p 157-160, 2001*

Gwyther R.L., M.T. Gladwin, R.H. Hart & M.Mee Aseismic stress transfer between shallow and medium depths in transition zones of the San Andreas Fault.. *EOS. (Trans. Am. Geo. Un.)*, 2001.

Gwyther R.L., M.T. Gladwin, R.H. Hart & M. Mee Sharpening our Image of Fault Processes: what Borehole Tensor Strain Observations can add to Seismic and Geodetic Studies. *Seis. Res. Lett.* 70(1), 255, 2000.

Gladwin, M.T., R.L. Gwyther, R.H. Hart, & M. Mee Borehole Tensor Strainmeter Arrays to Enhance our Imaging of Crustal Processes *EOS. (Trans. Am. Geo. Un.)*,48(17), , 2000

Gwyther, R.L., C.H. Thurber, M.T.Gladwin &M. Mee Seismic and Aseismic Observations of the 12th August 1998 San Juan Bautista, California M 5.3 earthquake, *Proc. 3rd Conf. on Tectonic Problems of the San Andreas Fault*, 2000

Gwyther R.L., M.T. Gladwin, R.H. Hart & M.Mee Propagating Aseismic Fault Slip events at Parkfield: What they tell us about fault processes at depths of 1km to 5 km. *EOS. (Trans. Am. Geo. Un.)*,81(48), p F1125, 2000.

Gladwin, M.T., R.L. Gwyther, R.H. Hart, & M.Mee Are linear strain rates between major strain events characteristic of transition zone regions of the San Andreas Fault *EOS. (Trans. Am. Geo. Un.)*, 81(48), p F921, 2000

Gladwin,M.T., Gwyther,R.L., & Hart,R.H.G., Addition of Strain to Targeted GPS Clusters-New Issues for Large Scale Borehole Strainmeter Arrays, *Proc. 2nd Plate Boundary Observatory Workshop*,1.17a-1.17e, *2000*

Langbein, J., Gladwin, M.T., & Gwyther,R.L., Extension of the Parkfield deformation array,*Proc. 2nd Plate Boundary Observatory Workshop*,2.45-2.49,2000

Thurber,C., Gladwin,M.T., Rubin,A., & DeMets,D.C., Focussed Observation of the San Andreas/Calaveras Fault intersection in the region of San Juan Bautista, California, *Proc. 2nd Plate Boundary Observatory Workshop*,2.75-2.79, 2000

Roeloffs,E., Gladwin,M.T., & Hart,R.H.G., Strain monitoring at the bend in the Cascadia Subduction Zone, *Proc. 2nd Plate Boundary Observatory Workshop*,4.36-4.40 2000

Steidl,J., Gladwin,M.T., Gwyther,R.L., & Vernon, F., Fault Processes on the Anza section of the San Jacinto Fault, *Proc. 2nd Plate Boundary Observatory Workshop*,2.70-2.74, 2000

Agnew,D., Wyatt, F., & Gladwin, M.T., Strainmeter Calibration, *Proc. 2nd Plate Boundary Observatory Workshop*, I1-I5, 2000

Langbein, J., Roeloffs,E., Gladwin,M.T.,& Gwyther R.L., Creepmeters on the San Andreas Fault System between San Francisco Bay and Parkfield, *Proc. 2nd Plate Boundary Observatory Workshop*, 2.40-2.44, 2000

Selected Previous Journal Publications

Langbein, J., R.L. Gwyther, R.H.G.Hart and M.T. Gladwin Slip-rate increase at Parkfield in 1993 detected by high-precision EDM and borehole tensor strainmeters *Geophys. Res. Lett.* 26(16) pp 2529-2532, 1999

Gwyther R.L., M.T. Gladwin and R.H.G. Hart Anomalous Shear Strain at Parkfield During 1993-94 *Geophys. Res. Lett. V 23 (18)* p 2425-2428, 1996

Hart R.H.G., M.T. Gladwin, R.L. Gwyther, D.C. Agnew and F.K. Wyatt Tidal Calibration of Borehole strain meters: Removing the effects of small-scale inhomogeneity *J. Geophys. Res., V101(B11), p25553-25571,* 1996

Linde A. T., M.T.Gladwin, M.J.S.Johnston, R.L.Gwyther & R.G.Bilham A Slow Earthquake Sequence near San Juan Bautista, California in December 1992. *Nature V. 383* p. 65-69 1996

Wyatt, F.K, Agnew, D.C. and Gladwin M.T. Continuous Measurements of Crustal Deformation for the 1992 Landers Earthquake Sequence. *Bull. Seis. Soc. Am*, Vol 84, No 3, 768-779, 1994.

Gladwin, M. T., Breckenridge, K.S.,Gwyther, R. L. and Hart, R. Measurements of the Strain Field Associated with Episodic creep events at San Juan Bautista, California. *J. Geophys. Res.*,Vol 99 (B3), 4559-4565, 1994.

Gladwin, M.T., Gwyther, R.L., Hart, R.H.G. and Breckenridge K.(1993) Measurements of the strain field associated with episodic creep events on the San Andreas fault at San Juan Bautista, California (1994*). J. Geophys. Res*. Vol 99 (B3), 4559-4565.

Linde A.T., Gladwin M.T. and Johnston M.J.S. (1992) The Loma Prieta Earthquake, 1989 and Earth Strain Tidal Amplitudes: An Unsuccessful Search for Associated Changes. *Geophysical Res. Let.* Vol 19 No.3 pp 317-320.

Gwyther R.L., Gladwin M.T. and Hart R.H.G. (1992) A Shear Strain Anomaly Following the Loma Prieta Earthquake. *Nature* Vol 356 No.6365 pp 142-144.

Gladwin,M.T., Gwyther R.L., Higbie J.W. and Hart R.G.(1991) A Medium Term Precursor to the Loma Prieta Earthquake? *Geophys. Res. Let.* Vol 18 No.8 pp 1377-1380.

Johnston, M.J.S., Linde, A.T. and Gladwin, M.T.(1990) Near-Field High Resolution Strain Measurements Prior to the October 18, 1989, Loma Prieta ML 7.1 Earthquake. *Geophysical Res. Let.* Vol 17 No.10 pp 1777-1780.

Gladwin, M.T., Gwyther, R., Hart, R., Francis, M., and Johnston, M.J.S., Borehole Tensor Strain Measurements in California. *J. Geophys. Res*. 92. B8 pp7981-7988, 1987. .

Johnston, M. J. S., Linde, A.T., Gladwin, M.T., and Borcherdt, R.D. Fault Failure with Moderate Earthquakes. *Tectonophysics*. 144, 189-206, 1987. .

Gladwin, M. T. and Hart, R. Design Parameters for Borehole Strain Instrumentation. *Pageoph.*,123, 59-88, 1985. .

Gladwin, M. T., High Precision multi component borehole deformation monitoring. *Rev.Sci.Instrum.*, 55 , 2011-2016, 1984. .

Gladwin, M. T. and Wolfe, J. Linearity of Capacitance Displacement Transducers. *J.Sc.Instr*. 46, 1099-1100, 1975. .

Non-Technical Summary

DEEP BOREHOLE TENSOR STRAIN MONITORING, NORTHERN CALIFORNIA

NEHRP Grant 99-HQ-GR-0060

Dr. M.T. Gladwin, Chief Research Scientist
Dr. R.L.Gwyther, Research Geophysicist

Commonwealth Scientific and Industrial Research Organisation
2643 Moggill Rd., Pinjarra Hills, QLD 4069, AUSTRALIA
phone +617 3212 4562
fax +617 3212 4455
II
seismology, geodesy, borehole geophysics

This project provides field observations of horizontal strain changes over timescales from minutes to years, critical to an understanding of fault processes associated with earthquakes along the San Andreas and Hayward fault systems. The project continues a program of maintenance and analysis of deep borehole tensor strain instrumentation initiated at San Juan Bautista and Pinon Flat Observatory in late 1983. Three further instruments were deployed near Parkfield in central California in 1986, and two instruments were deployed near the Hayward fault in 1992. A series of episodic strain events associated with surface creep events have been observed at Parkfield, similar to those previously reported at San Juan Bautista. The occurrence of these episodic events is directly related to longer term changes in strain rate at these sites, and suggests processes for stress transfer from medium to shallow depths of the fault. This project runs in parallel with a maintenance project covering two further instruments in Southern California.